Tracking Loop and Modulation Format Considerations for High Rate Telemetry

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Tracking loops and modulation formats for DSN telemetry rates in the tens of megasymbols per second region are considered. It is shown that for high rate telemetry, subcarriers should not be used and suppressed carrier modulation should be used. It is then shown that the current DSN receivers can be used for tracking suppressed carrier signals with only minor modifications and that normal doppler tracking operations are unaffected by such changes. Finally, we show that the existing DSN, augmented by a megasymbol telemetry demodulator assembly can be used to process simultaneous high rate telemetry and ranging signals using an interplex modulation format which results in significant advantages to both telemetry and ranging.

I. Introduction

The DSN emerged at a time when weak signals and low data rates dominated. As a result, residual carrier phase modulation schemes with phase locked loops tracking the residual carrier component were employed. However, over the years technological advances in antennas, transmitters and signal processing have caused a marked increase in the available signal power and hence the achievable data rates. In fact essentially all of the current or near future deep space missions are already operating at or near the upper limit of the current DSN data rate capability.

The DSN, under the auspices of advanced systems, is currently involved in new high rate telemetry system designs which will push the DSN data rate capability into the tens of megabits per second region. Such telemetry reception capabilities would greatly enhance future missions such as Venus Orbiting Imaging Radar (VOIR) by greatly improving the attainable mapping resolution. However when designing any such system one should re-examine the assumptions upon which the earlier low rate system was based to see how many, or even if any, of them apply to the present problem. For example one should ask if subcarriers should still be used or if it is still necessary to retain a residual carrier for the purpose of tracking. In this paper we will examine the implications of such questions as well as assess the impacts of proposed new concepts on the current DSN.

II. Are Subcarriers Needed?

When the DSN operated at 8 bps using residual carrier modulation it was necessary to place the data modulation on subcarriers. This was necessary since without the subcarrier most of the data power would fall within the bandwidth of, and be tracked out by, the carrier phase locked loop. Also, at low data rates a carrier tracking loop is usually much closer to threshold so that any additional disturbance in the loop can be quite serious.

At the higher data rates the picture is quite different. In order to support the higher data rates one must have more signal power. Thus the signal (and hence carrier power) to noise density ratio is very much larger. This results in a greatly improved carrier loop SNR. Also, the data signal spectrum is broad so that the part which is contained in the loop bandwidth (when subcarriers are not used) appears as white noise. Its effect is averaged out and degrades the tracking loop performance very little. This suggests that subcarriers are not needed in high data rate systems.

A much stronger statement can be made when considering the disadvantages of subcarriers. Consider a telemetry system which is to operate at 25 Mbps. Assume also that subcarriers are to be used. The DSN standard is for the subcarrier to be a square wave and have a frequency at least 1.5 times the data rate. Thus, a 37.5 MHz subcarrier is required. However, in order to keep the SNR degradation down to a tolerable level it is necessary to process a sufficient number of subcarrier harmonics; say to the fifth harmonic. In this example the resulting bandwidth is ±188 MHz on either side of the carrier and is larger than the current bandwidth allocation of 100 MHz at X-band. Therefore we see that subcarriers cannot be used at the higher data rates.

III. Is Residual Carrier Needed?

We saw in the last section that subcarriers should be eliminated in high rate systems. We will now consider the desirability of using residual carrier modulation.

Consider first a residual carrier signal of the form:

$$\chi(t) = \sqrt{2}\, A \cos\left[\omega_0 t - \theta D(t)\right] + n(t)$$

where A is the signal amplitude, ω_0 is the carrier angular frequency, θ the modulation angle ($\theta < 90°$), $D(t)$ is the binary data modulation (no subcarrier), and $n(t)$ is white gaussian noise. When this signal is tracked by a phase locked loop having a tracking error of ϕ, the resulting phase detector output $E(t)$ is (assuming ϕ is small):

$$E(t) = A(\cos\theta)\phi + A \sin\theta\, D(t) + n^1(t)$$

where $n^1(t)$ is the equivalent white gaussian noise at baseband. We note that the first term of $E(t)$ represents the phase error signal for tracking purposes, whereas the second term is the data dependent self noise resulting from the fact that no subcarrier was used. Since the data rate is high the energy of the data dependent interference will be spread over a wide bandwidth and hence over the tracking loop bandwidth will appear as a white noise. The equivalent two-sided spectral density $N_I(0)$ of this interference is given by:

$$N_I(0) = A^2 \sin^2\theta\, T_s = \frac{A^2\, T_s \sin^2\theta\, N_0}{N_0} = R\, N_0$$

where T_s is the symbol time duration, N_0 is the one-sided thermal noise spectral density and R is the symbol SNR. Then, if we compute the loop signal to noise ratio ρ_L we have that

$$\rho_L = \frac{A^2 \cos^2\theta}{2B_L\left(\frac{N_0}{2} + R N_0\right)} = \frac{A^2}{N_0 B_L}\left(\frac{\cos^2\theta}{1+2R}\right)\left(\begin{matrix}\text{Residual}\\ \text{Carrier}\end{matrix}\right)$$

where B_L is the one-sided loop bandwidth. We see that the loop SNR can be expressed as the product of the total signal power to noise in the loop bandwidth ratio and a degradation factor:

$$\beta = \left(\frac{\cos^2\theta}{1+2R}\right)$$

representing the effects of modulation format and self-noise interference. Note that if a subcarrier had been used the $2R$ term would have disappeared leaving the familiar result for the present phase locked loop performance.

We are interested in evaluating the degradation factor β for typical high rate applications. Table 1 lists the value of β for several values of SNR and for the case where $\theta = 80°$. Also shown in this table is a breakdown of the value of β into the contributing factors of self-interference and modulation loss.

From Table 1 we see that the penalty for using residual carrier is from 20 to 30 dB, 15 dB of which comes from the modulation loss.

Consider now a suppressed carrier signal of the form:

$$\chi(t) = \sqrt{2}\; A\, D(t) \cos\omega_0 t + n(t)$$

where $n(t)$ is narrow band white gaussian noise. Let $\chi(t)$ be applied to a Costas type tracking loop of the kind shown in

Fig. 1. Assume that the tracking reference signal has a phase error of ϕ radians as shown in the figure. The outputs of the arm filters $\chi_c(t)$ and $\chi_s(t)$ are given by:

$$\chi_c(t) = \sqrt{\alpha}\, A\, D(t) \cos\phi + n_c(t)$$

and

$$\chi_s(t) = -\sqrt{\alpha}\, A\, D(t) \sin\phi + n_s(t)$$

Here α represents the fraction of the data signal spectrum which is passed by the arm filters and $n_s(t)$ and $n_c(t)$ are the low pass quadrature noise terms, each with spectral density $N_0/2$ and one-sided bandwidth B. If the arm filters are ideal then:

$$\alpha = \frac{2}{\pi}\left\{ \mathrm{Si}(2\pi BT_s) - \frac{\sin^2(\pi BT_s)}{\pi BT_s} \right\}$$

which depends on the symbol time-bandwidth product. Typical values for α are given in Table 2.

To produce an error control signal the cross product of χ_c and χ_s is taken. The resulting error signal is (assuming ϕ is small)

$$E(t) = \alpha A^2\phi + \sqrt{\alpha}\, AD(t)\,[n_c(t)\sin\phi - n_s(t)\cos\phi]$$

$$+\, n_s(t)\, n_c(t) = \alpha A^2\,\phi + N_1(t) + N_2(t)$$

The first term represents the phase tracking signal whereas the second and third terms represent the data interference and thermal disturbance respectively. The null spectral density of $N_1(t)$ is:

$$S_{N1}(0) = \frac{\alpha A^2 N_0}{2}$$

Whereas the corresponding result for $N_2(t)$ is:

$$S_{N2}(0) = \frac{N_0^2 B}{2}$$

The tracking loop SNR is then found to be:

$$\rho_L = \frac{\alpha^2 A^4}{2B_L\left(\dfrac{\alpha N_0 A^2}{2} + \dfrac{N_0^2 B}{2}\right)}$$

$$= \frac{A^2}{N_0 B_L}\left(\frac{\dfrac{R\alpha^2}{BT_s}}{1 + \dfrac{R\alpha}{BT_s}}\right) \quad \begin{pmatrix}\text{Suppressed}\\ \text{Carrier}\end{pmatrix}$$

Note that as in the case of residual carrier the loop SNR for the suppressed carrier system is the product of A^2/N_0B_L and the degradation term

$$\beta' = \frac{\dfrac{R\alpha^2}{BT_s}}{1 + \dfrac{R\alpha}{BT_s}}$$

However, in this case the degradation factor depends on both the symbol SNR as well as the BT_s product. (α is also a function of BT_s.)

Table 3 lists the values of β' for several values of R and BT_s products.

Comparison of Table 3 with Table 1 shows that a significant improvement in tracking SNR results from suppressed carrier operation. For example, at $BT_s = 2$, the case of most practical interest, the suppressed carrier loop enjoys a 15 to 30 dB advantage over the residual carrier scheme.

IV. Is a New Receiver Needed?

To convert from residual to suppressed carrier modulation may be desirable from a technical performance standpoint but may not be economically feasible if a complete new receiver is needed. Fortunately it is possible to use the existing receivers for tracking suppressed carrier signals with only a slight modification. Figure 2a shows a block diagram of the block IV receiver. Similar results can be easily extended to the block III receiver if desired. The receiver transforms the received signal through a series of intermediate frequency conversions to an IF signal compatible with the final IF phase detector. The phase detector output is then filtered and used to control the VCO.

Consider now the block diagram shown in Fig. 2b. This shows how a megasymbol telemetry demodulator can be used along with the block IV receiver in a suppressed carrier mode. The receiver still makes the IF conversions as it did in the previous figure. However, the control of the VCO is accomplished now by the loop filter in the demodulator which operates from the 55 MHz IF. (This IF was selected since it has enough bandwidth to support megasymbol telemetry.) The only change to the receiver necessary for this configuration is the addition of the switch at the input to the VCO.

V. What About Doppler and Ranging?

Referring again to Fig. 2 we see that the receiver supplied signal to the doppler extraction equipment comes from the receiver VCO output. Since this VCO is common to both the residual and suppressed carrier configurations then no change is necessary in the hardware in order to maintain the doppler tracking capability. Actually the doppler tracking ability will be enhanced by the fact that the loop SNR will be greater, thus reducing the doppler jitter. There is, however, one minor impact to the doppler processing software as a result of going to suppressed carrier. The present systems occasionally experience tracking cycle slips which result in phase jumps of ±360 degrees. In suppressed carrier systems there are two stable tracking lock points so that 1/2 cycle slips are possible. These, however, should be quite infrequent due to the improved tracking.

With regard to ranging we note first that at present, telemetry and ranging signals are sent in effectively a frequency division multiplexed format. This is accomplished by allowing the telemetry signal to occupy the lower region of the modulation spectrum and placing the ranging signal in the upper region. Actually, in more recent years the increasing telemetry rates have resulted in a significant degree of spectral overlap of these signals.

For suppressed carrier modulation this multiplexing method is not desirable, for two reasons; first of all the telemetry signal spectrum is quite broad and will most likely occupy all of the receiver IF bandwidth; second for suppressed carrier modulation this modulating signal would result in a transmitted signal with a nonuniform envelope which is undesirable from a power amplification standpoint. There is, however, an alternate method by which these two signals can be multiplexed which (1) eliminates interference between the telemetry and ranging signals, (2) allows complete freedom in selecting both the telemetry and ranging signal rates/frequencies (provided each one separately does not exceed the available IF bandwidth), and (3) allows processing with current DSN equipment. The technique simply involves modulating one component of a carrier with the telemetry signal and modulating a quadrature component of the carrier with the ranging signals. Both modulations are suppressed carrier in nature and the resulting signals are then summed using amplitudes appropriate for the necessary telemetry and ranging SNR requirements. Figure 3 shows the structure of the carrier modulator.

That this signal has the properties stated above can be seen quite easily. Interference resulting from spectral overlap is eliminated since the ranging and telemetry signals are in phase quadrature and can be easily isolated using a coherent receiver (even when their spectra overlap). Since they are isolated by phase then the presence of one does not in any way restrict the use of the other. Finally, with regard to processing, we note that the telemetry can be demodulated in the megabit-demodulator assembly as shown in Fig. 2b. Likewise the ranging signal *could* be demodulated on the other arm of the megabit-demodulator assembly. Unfortunately, this would result in a baseband ranging signal for which the DSN does not have a detector. However, recall that the receiver IF chain is still very much intact. As a result, the ranging signal can be processed from the 10 MHz IF in exactly the same way it is at present by simply ensuring that the reference in the Planetary Ranging Assembly (PRA) or MU II ranging machines are adjusted for the appropriate phase. This can easily be accomplished by a pretrack calibration.

The modulation scheme described above is really not a new scheme. It was originally developed at JPL as a suppressed carrier version of interplex modulation (Refs. 1 and 2). Its utility has been demonstrated on MVM-73 (in the residual carrier mode) and more recently has been used in the suppressed carrier mode on the Space Shuttle under the name of unbalanced quadraphase. It was demonstrated for MVM-73 that interplex modulation involving two telemetry signals could be processed by the existing DSN by proper phasing of the reference signals. Likewise, the interplex modulation of telemetry and ranging can be processed by the DSN with proper phasing. Finally, the suppressed carrier tracking configuration of Fig. 2b is also appropriate for tracking the suppressed carrier versions of interplex modulation (Refs. 1, 3 and 4).

VI. Conclusions

We have shown that to go to high data rates it is necessary to eliminate the use of subcarriers. We then demonstrated that a significant advantage in tracking loop SNR would result for changing from residual to suppressed carrier modulation. This gain in loop SNR is extremely desirable since it allows one to broaden the tracking loop bandwidth and hence simplifies the operational activities needed for signal acquisition without sacrificing tracking performance. Also a stronger loop SNR means that the tracking loop is much less likely to be knocked out of lock by external RFI and results in improved navigation by means of reduced doppler jitter.

We next demonstrated that the current block IV receivers (or the block III receivers) could still be used in conjunction with the megasymbol demodulator assembly to track suppressed carrier signals. We next found that the doppler system was quite insensitive to the change to suppressed carrier with the only impact being the possibility of half cycle slips occurring, as well as full cycle slips. Finally we found that simultaneous telemetry and ranging, although impractical in the present format at high telemetry rates, could be easily handled by an unbalanced quadraphase signal format and that the resulting signal could be quite adequately processed by the existing DSN if simply augmented by the megasymbol demodulator assembly.

References

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2. Butman, S., and Timor, U., "Interplex – An Efficient Multichannel PSK/PM Telemetry System", *IEEE Transactions on Communications*, Volume COM-20, No. 3, June 1972, pp. 415-419.
3. Levitt, B. K., Lesh, J. R., and Springett, J. C., "Shuttle/TDRSS Ku-Band Telemetry Study: Final Report" JPL internal report No. 900-742, Jet Propulsion Laboratory, Pasadena, California, April 5, 1976.
4. Lesh, J. R., "Costas Loop Tracking of Unbalanced QPSK Signals" submitted for presentation at the IEEE International Conference on Communications," Toronto, Canada, June 1978.

Table 1. Loop SNR degradation factor for residual carrier and $\theta = 80°$

R, dB	β, dB	$\frac{1}{1 + 2R}$, dB	$\text{Cos}^2\,\theta$, dB
0	-20.0	-4.8	-15.2
4	-23.0	-7.8	-15.2
10	-28.4	-13.2	-15.2

Table 2. Data power fraction α

BT_s	1	2	3	4	5
α	.903	.950	.966	.975	.980

Table 3. Loop SNR degradation factor for suppressed carrier tracking

R, dB	β', dB				
	$BT_s = 1$	$BT_s = 2$	$BT_s = 3$	$BT_s = 4$	$BT_s = 5$
0	-3.68	-5.14	-6.28	-7.19	-7.94
4	-2.03	-2.87	-3.65	-4.31	-4.90
10	-0.90	-1.05	-1.32	-1.60	-1.88

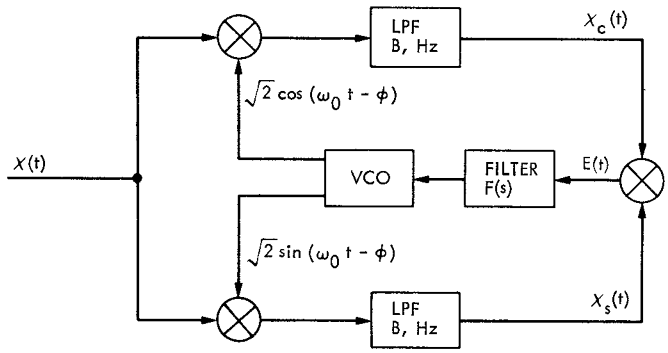

Fig. 1. Costas tracking loop

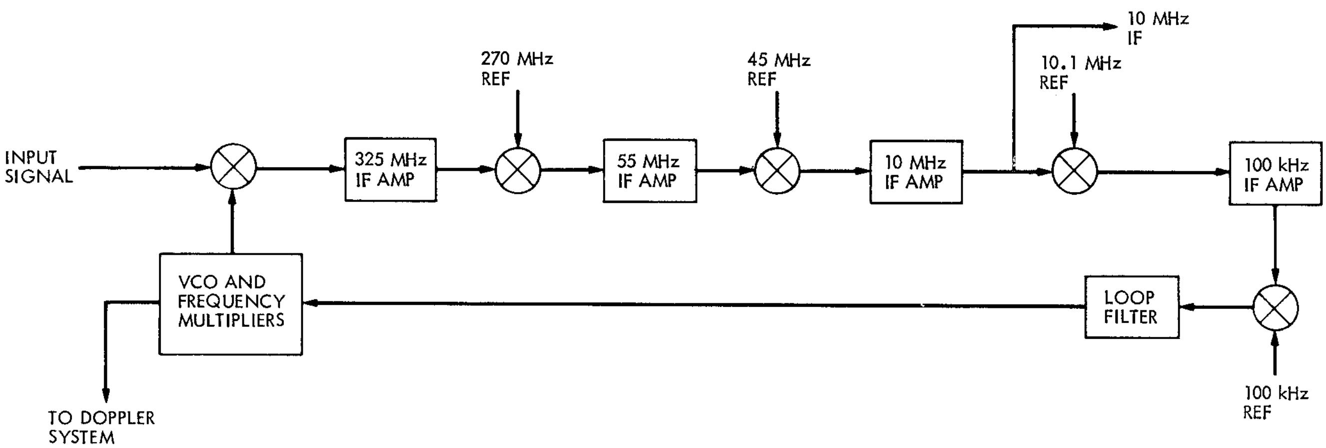

Fig. 2a. Simplified block IV receiver block diagram

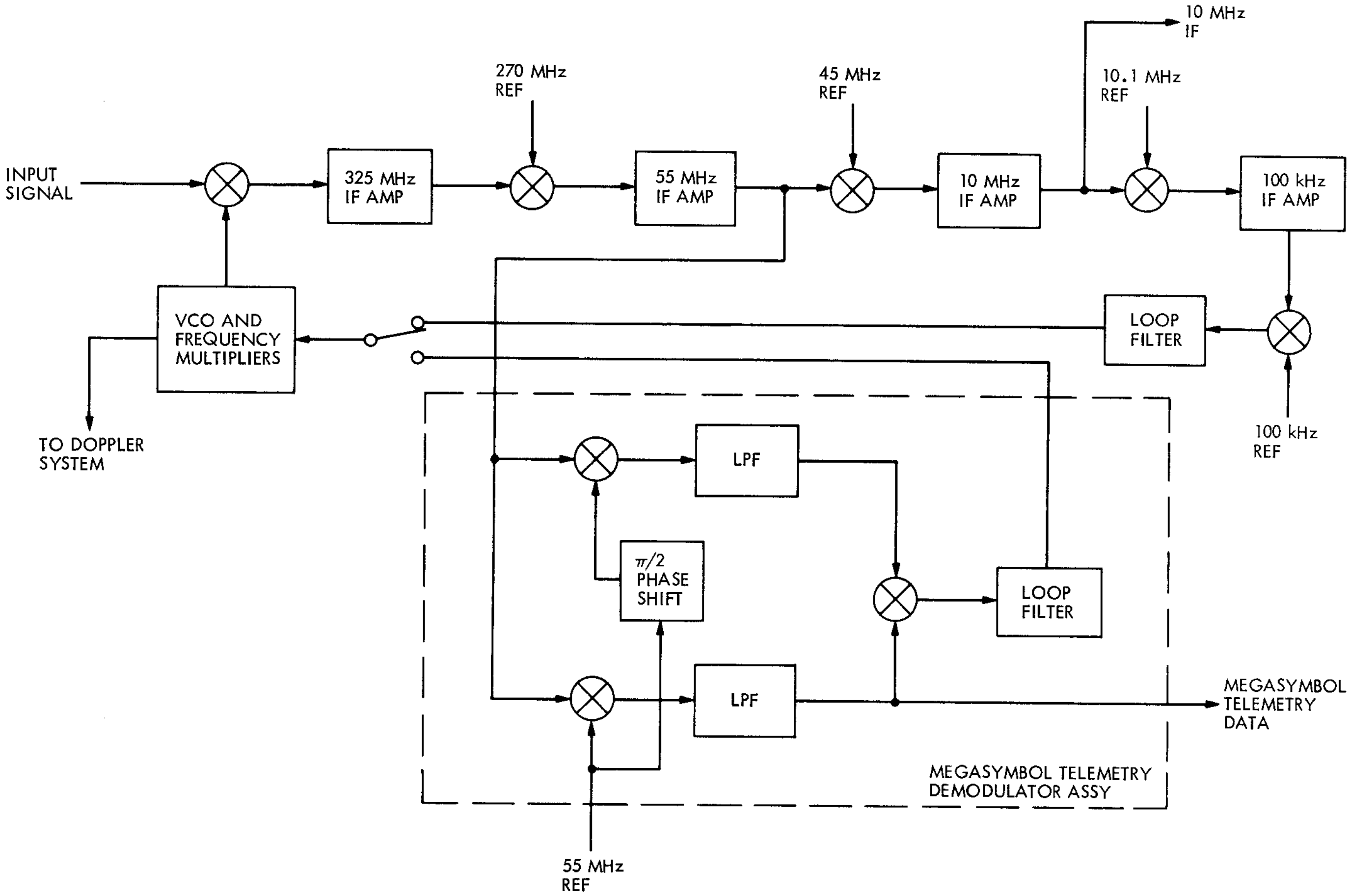

Fig. 2b. Modified block IV receiver block diagram for suppressed carrier

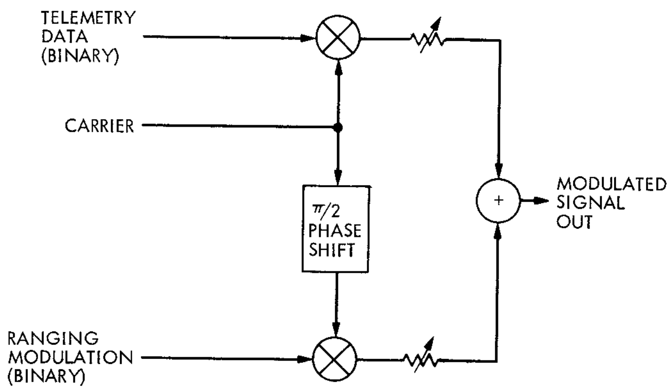

Fig. 3. Unbalanced QPSK modulator